THE ASTROPHYSICAL JOURNAL, 612:L101–L104, 2004 September 10

CONSTRAINING Ω_M AND DARK ENERGY WITH GAMMA-RAY BURSTS

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Received 2004 June 25; accepted 2004 July 23; published 2004 August 17

ABSTRACT

An $E_{\gamma,\,\rm jet} \propto E_p'^{1.5}$ relationship with a small scatter for current gamma-ray burst (GRB) data was recently reported, where $E_{\gamma,\,\rm jet}$ is the beaming-corrected gamma-ray energy and E_p' is the νF_ν peak energy in the local observer frame. By considering this relationship for a sample of 12 GRBs with known redshift, peak energy, and break time of afterglow light curves, we constrain the mass density of the universe and the nature of dark energy. We find that the mass density $\Omega_M = 0.35^{+0.15}_{-0.15}$ (at the 1 σ confidence level) for a flat universe with a cosmological constant, and the w parameter of an assumed static dark energy equation of state $w = -0.84^{+0.57}_{-0.83}$ (1 σ). Our results are consistent with those from Type Ia supernovae. A larger sample established by the upcoming *Swift* satellite is expected to provide further constraints.

Subject headings: cosmological parameters — cosmology: observations — gamma rays: bursts

Online material: color figure

1. INTRODUCTION

Type Ia supernovae (SNe Ia) have been playing an important role in modern cosmology. Early observations of SNe Ia at redshift $z < 1$ strongly suggest that the expansion of the universe at the present time is accelerating (Riess et al. 1998; Perlmutter et al. 1999). Since then, the nature of dark energy (with negative pressure) that drives cosmic acceleration has been one of the greatest mysteries in modern cosmology (for reviews, see Peebles & Ratra 2003; Padmanabhan 2003). Recent observations of 16 higher redshift (up to $z \simeq 1.7$) SNe Ia present conclusive evidence that the universe had once been decelerating (Riess et al. 2004). These newly discovered objects, together with previous reported SNe Ia, have been used to provide further constraints on both the expansion history of the universe and the equation of state (EOS) of a dark energy component (Riess et al. 2004; Wang & Tegmark 2004; Daly & Djorgovski 2004; Feng et al. 2004).

Gamma-ray bursts (GRBs) are the brightest electromagnetic explosions in the universe. It has been widely believed that they should be detectable out to very high redshifts (Lamb & Reichart 2000; Ciardi & Loeb 2000; Bromm & Loeb 2002). Gamma-ray photons with energy from tens of keV to MeV, if produced at high redshifts, suffer from no extinction before they are detected. These advantages over SNe Ia would make GRBs an attractive probe of the universe. Schaefer (2003) derived the luminosity distances of nine GRBs with known redshifts by using two luminosity indicators (the spectral lag and the variability). He obtained the first GRB Hubble diagram with the 1 σ constraint on the mass density $\Omega_M < 0.35$.

A correlation between the isotropic-equivalent gamma-ray energy ($E_{\gamma,\,\rm iso}$) and the νF_ν peak energy (E_p') in the local observer frame, $E_p' \propto E_{\gamma,\,\rm iso}^{1/2}$, was discovered by *BeppoSAX* observations (Amati et al. 2002; Yonetoku et al. 2004) and confirmed by *High Energy Transient Explorer 2* observations (Sakamoto et al. 2004; Lamb et al. 2004). It holds not only among BATSE GRBs (Lloyd-Ronning & Ramirez-Ruiz 2002) but also within one GRB (Liang et al. 2004). Its possible explanations include the synchrotron mechanism in relativistic shocks (Zhang & Mészáros 2002; Dai & Lu 2002) and the emission from off-axis relativistic jets (Yamazaki et al. 2004; Eichler & Levinson 2004). However, the dispersion around this correlation is too large to obtain useful information on the universe from the current GRB sample.

Ghirlanda et al. (2004) recently found a new relationship between the beaming-corrected gamma-ray energy ($E_{\gamma,\,\rm jet}$) and the local-observer peak energy, $E_{\gamma,\,\rm jet} \propto E_p'^{1.5}$, with a small scatter for current GRB data, suggesting that GRBs are a promising probe of the universe. In principle, this relationship can be derived from the $E_p' \propto E_{\gamma,\,\rm iso}^{1/2}$ correlation combined with the afterglow jet model. In this Letter, we constrain the mass density of the universe and the nature of dark energy by considering this relationship with a sample of 12 GRBs with known redshift, peak energy, and break time of afterglow light curves. We show that GRBs appear to provide an independent and interesting probe of fundamental quantities of the universe.

2. SAMPLE SELECTION AND STANDARD CANDLES

By searching for GRBs in the literature, we have found a total of 14 bursts of which redshift z, observed peak energy E_p, and break time t_j of afterglow light curves are available. Table 1 lists a sample of 12 GRBs, but the other two events, GRBs 990510 and 030226, are not included. The reason is as follows: the analysis of this Letter and Ghirlanda et al. (2004) is based on the afterglow jet model (Rhoads 1999; Sari et al. 1999). In this model, a relativistic jet, after emitting a fraction η_γ of its kinetic energy into prompt gamma rays, expands in a homogeneous medium with number density of n. As the jet sweeps up more and more medium matter, its Lorentz factor declines. When the Lorentz factor equals the inverse of the jet's half-opening angle θ, the afterglow light curve presents a break. However, this model cannot well fit the afterglow data of these two bursts, because the predicted break spans about 2 orders of magnitude in time when light-travel time effects are taken into account, and thus the theoretical light curve is too smooth to be consistent with the observed sharpness (Rhoads & Fruchter 2001; Wei & Lu 2002). For GRB 990510, the required spectral index of the electrons is less than 2, being inconsistent with the shock acceleration theory (Wei & Lu 2002). In addition, the afterglow data of GRB 030226 suggest

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TABLE 1
SAMPLE OF GRBS

GRB	Redshift	$E_p(\sigma_{E_p})$[a] (keV)	α[a]	β[a]	$S_\gamma(\sigma_{S_\gamma})$[b] (ergs cm^{-2})	Range[b] (keV)	$t_j(\sigma_{t_j})$[c] (days)	$n(\sigma_n)$[d] (cm^{-3})	References[e]
970828	0.957	297.9(59.3)	−0.7	−2.07	9.6E−5(0.9)	20–2000	2.2(0.4)	3(0.33)	1, 2, 3
980703	0.966	255.3(50.9)	−1.31	−2.39	2.3E−5(0.2)	20–2000	3.4(0.5)	28(10)	2, 4, 5
990123	1.6	780.8(61.9)	−0.89	−2.45	3.0E−4(0.4)	40–700	2.04(0.46)	3(0.33)	6, 7, 8
990705	0.843	188.8(15.2)	−1.05	−2.2	7.5E−5(0.8)	40–700	1.0(0.2)	3(0.33)	7, 9, 10
990712	0.43	65.0(10.5)	−1.88	−2.48	6.5E−6(0.3)	40–700	1.6(0.2)	3(0.33)	7, 11, 12
991216	1.02	317.3(63.4)	−1.234	−2.18	1.9E−4(0.2)	20–2000	1.2(0.4)	4.7(2.3)	2, 13, 14, 15
011211	2.14	59.2(7.6)	−0.84	−2.3	5.0E−6(0.5)	30–400	1.50(0.02)	3(0.33)	7, 16, 17
020124	3.2	110.0(22.0)	−1	−2.3	6.8E−6(0.7)	30–400	3.0(0.4)	3(0.33)	18, 19, 20
020405	0.69	192.5(53.8)	0	−1.87	7.4E−5(0.7)	15–2000	1.67(0.52)	3(0.33)	21, 22
020813	1.25	211.0(42.0)	−1.05	−2.3	1.0E−4(0.1)	30–400	0.43(0.06)	3(0.33)	23, 24, 25
030328	1.52	109.9(21.8)	−1	−2.3	2.6E−5(0.2)	30–400	0.8(0.1)	3(0.33)	20, 24, 26
030329	0.1685	67.6(2.6)	−1.26	−2.28	1.1E−4(0.1)	30–400	0.5(0.1)	1(0.11)	27, 28, 29

[a] The spectral parameters fitted by the Band function.
[b] The fluence and error observed in the corresponding energy range.
[c] The observed break time and error of the afterglow light curve.
[d] The medium density and error from afterglow fittings; if not available the value of n is taken to be 3 ± 0.33 cm^{-3}.
[e] References in order for redshift, spectral data, t_j, and n.

REFERENCES.—(1) Djorgovski et al. 1999; (2) Jimenez et al. 2001; (3) Djorgovski et al. 2001; (4) Djorgovski et al. 1998; (5) Frail et al. 2003; (6) Hjorth 1999; (7) Amati et al. 2002; (8) Kulkarni et al. 1999; (9) Amati et al. 2000; (10) Masetti et al. 2000; (11) Galama et al. 1999; (12) Bjornsson et al. 2001; (13) Vreeswijk et al. 1999a; (14) Halpern et al. 2000; (15) Panaitescu & Kumar 2002; (16) Andersen et al. 2000; (17) Jakobsson et al. 2003; (18) Hjorth et al. 2003; (19) Barraud et al. 2003; (20) Ghirlanda et al. 2004; (21) Masetti et al. 2003; (22) Price et al. 2003; (23) Price et al. 2002; (24) Atteia 2003; (25) Barth et al. 2003; (26) Rol et al. 2003; (27) Greiner et al. 2003; (28) Vanderspek et al. 2004; (29) Berger et al. 2003.

that its environment might be a low-density wind rather than a constant-density medium, also conflicting with the model (Dai & Wu 2003).

According to the afterglow jet model (Sari et al. 1999), the jet's half-opening angle is given by $\theta = 0.161(1+z)^{-3/8} t_{j,d}^{3/8} E_{\gamma,\mathrm{iso},52}^{-1/8} n_0^{1/8} \eta_\gamma^{1/8}$, where $E_{\gamma,\mathrm{iso},52} = E_{\gamma,\mathrm{iso}}/10^{52}$ ergs, $t_{j,d} = t_j/1$ day, $n_0 = n/1$ cm^{-3}, and $\eta_\gamma = 0.2$ (Frail et al. 2001). Only for a few bursts in Table 1 was the medium density obtained from broadband modeling of the afterglow emission (e.g., Panaitescu & Kumar 2002). For those bursts with unknown n, we assume the median density $n \simeq 3$ cm^{-3} as in Ghirlanda et al. (2004). The isotropic-equivalent gamma-ray energy of a GRB is calculated by

$$E_{\gamma,\mathrm{iso}} = \frac{4\pi d_L^2 S_\gamma k}{1+z}, \qquad (1)$$

where S_γ is the fluence (in units of ergs cm^{-2}) received in some observed bandpass and k is the factor that corrects the observed fluence to the standard rest-frame bandpass (1–10^4 keV; Bloom et al. 2001). For a Friedmann-Robertson-Walker (FRW) cosmology with mass density Ω_M and vacuum energy density Ω_Λ, the luminosity distance in equation (1) is

$$d_L = c(1+z)H_0^{-1}|\Omega_k|^{-1/2}\,\mathrm{sinn}\,\Big\{|\Omega_k|^{1/2} \times \int_0^z dz[(1+z)^2(1+\Omega_M z) - z(2+z)\Omega_\Lambda]^{-1/2}\Big\}, \qquad (2)$$

where c is the speed of light and $H_0 \equiv 100\ h$ km s^{-1} Mpc^{-1} is the present Hubble constant (Carroll et al. 1992). In equation (2), $\Omega_k = 1 - \Omega_M - \Omega_\Lambda$, and "sinn" is sinh for $\Omega_k > 0$ and sin for $\Omega_k < 0$. For $\Omega_k = 0$, equation (2) turns out to be $c(1+z)H_0^{-1}$ times the integral. In this section, we assume a flat universe (i.e., $\Omega_k = 0$) because of both an expected consequence of inflation and the observed characteristic angular size scale of the cosmic microwave background fluctuations (Spergel et al. 2003 and references therein).

From equations (1) and (2), we obtain the beaming-corrected gamma-ray energy $E_{\gamma,\mathrm{jet}} = (1-\cos\theta)E_{\gamma,\mathrm{iso}}$; that is,

$$E_{\gamma,\mathrm{jet}} \simeq 1.30 \times 10^{50}(1+z)^{-3/4} t_{j,d}^{3/4} E_{\gamma,\mathrm{iso},52}^{3/4} n_0^{1/4} \eta_\gamma^{1/4}\ \mathrm{ergs}. \qquad (3)$$

Figure 1 plots $E_{\gamma,\mathrm{jet}}$ versus E'_p for the GRB sample listed in Table 1, with $\Omega_M = 0.27$, $\Omega_\Lambda = 0.73$, and $h = 0.71$. We find that $E_{\gamma,\mathrm{jet}}$ and E'_p are strongly correlated with a correlation coefficient $r_s = 0.99 \pm 0.08$ (with a probability of less than 10^{-4}). The best fit is $(E_{\gamma,\mathrm{jet}}/10^{50}$ ergs$) = (1.12 \pm 0.12)(E'_p/100\ \mathrm{keV})^{1.50\pm0.08}$ with a reduced $\chi^2_{\mathrm{dof}} = 0.53$. We note this power to be insensitive to Ω_M. In addition, although the peak energy E'_p and the low-energy spectral index α in Table 1 appear to evolve with redshift (Amati et al. 2002), this evolution does not affect the above relation as shown in Figure 1. These results suggest that GRBs are standard candles.

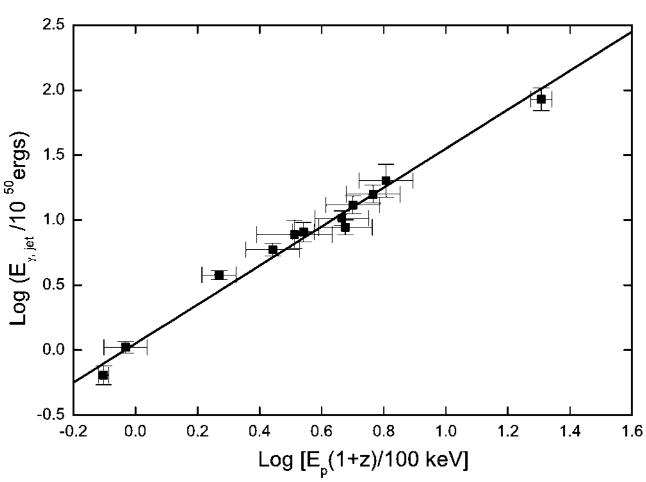

FIG. 1.—Beaming-corrected gamma-ray energy vs. local-observer peak energy for the GRB sample listed in Table 1. The line is the best fit.

3. HUBBLE DIAGRAM AND COSMOLOGICAL CONSTRAINTS

We first derive the observed luminosity distance from the GRB sample. Considering a relationship $(E_{\gamma,\mathrm{jet}}/10^{50}$ ergs$) =$

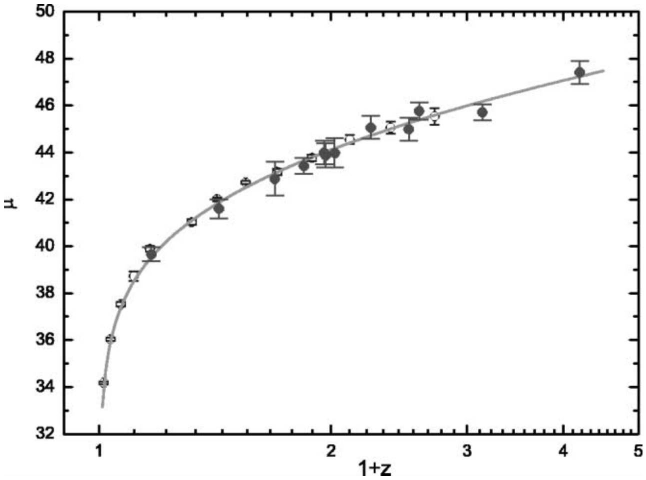

FIG. 2.—Hubble diagrams for the GRB sample (*filled circles*, for $C = 1.12$) and the binned SN Ia data from Riess et al. (2004; *open circles*). The line corresponds to a flat cosmology with $\Omega_M = 0.27$ and $h = 0.71$. [*See the electronic edition of the Journal for a color version of this figure.*]

$C(E'_p/100\ \mathrm{keV})^{1.5}$ (where C is a dimensionless parameter), we obtain

$$d_L = 2.37 \times 10^{23} \frac{(1+z)^2 C^{2/3} E_p}{(kS_\gamma t_{j,d})^{1/2}(n_0\eta_\gamma)^{1/6}}\ \mathrm{cm}, \tag{4}$$

where $E_p \equiv E'_p/(1+z)$ is in units of keV. Thus, the observed distance modulus of a GRB is $\mu_{\rm ob} = 5\log(d_L/10\ \mathrm{pc})$ with an error of

$$\sigma_{\mu_{\rm ob}} = 2.17\left[\left(\frac{\sigma_{E_p}}{E_p}\right)^2 + \left(\frac{\sigma_{S_\gamma}}{2S_\gamma}\right)^2 + \left(\frac{\sigma_{t_j}}{2t_j}\right)^2 + \left(\frac{\sigma_n}{6n}\right)^2\right]^{1/2}, \tag{5}$$

where σ_{E_p}, σ_{S_γ}, σ_{t_j}, and σ_n are the errors in the peak energy, fluence, break time, and medium density of the GRB, respectively.

We plot a Hubble diagram of our GRB sample in Figure 2 based on equations (4) and (5). This figure also presents a Hubble diagram of the current SNe Ia sample. Both Hubble diagrams are consistent with each other. However, GRBs and SNe Ia have mean uncertainties of 0.09 and 0.05 in the log of the distance, respectively, and thus GRBs are about twice worse in accuracy than SNe.

For an FRW cosmology with Ω_M and Ω_Λ, equation (2) gives the theoretical distance modulus $\mu_{\rm th} = 5\log(d_L/10\ \mathrm{pc})$. The likelihood for these cosmological parameters can be determined from a χ^2 statistic, where

$$\chi^2(h, \Omega_M, \Omega_\Lambda;\ C) = \sum_i \frac{[\mu_{\rm th}(z_i;\ h, \Omega_M, \Omega_\Lambda) - \mu_{{\rm ob},i}(C)]^2}{\sigma^2_{\mu_{{\rm ob},i}}}. \tag{6}$$

We consider all possible values of the parameters h and C to be $h \in (0.68, 0.75)$ (Bennett et al. 2003) and $C \in (1.00, 1.24)$ (see § 2). The confidence regions in the Ω_M-Ω_Λ plane can be found through marginalizing the likelihood functions over h and C (i.e., integrating the probability density $P \propto e^{-\chi^2/2}$ for all values of h and C). We plot contours of likelihood (from 1 to 3 σ) for unknown curvature Ω_k in Figure 3. As shown for a flat universe, with the current sample, $\Omega_M < 0.62$ (at the 2 σ confidence level), and the 1 σ contour contains the $(\Omega_M, \Omega_\Lambda) = (0.27, 0.73)$ point corresponding to the "concordance" model. We measure $\Omega_M = 0.35^{+0.15}_{-0.15}$ (1 σ).

There are several alternative approaches to calculate the luminosity distance (see also Riess et al. 2004). We here consider a flat universe and a constant EOS, $w = P_{\rm de}/\rho_{\rm de}c^2$, of a dark energy component (Garnavich et al. 1998; Perlmutter et al. 1999). In this case we have

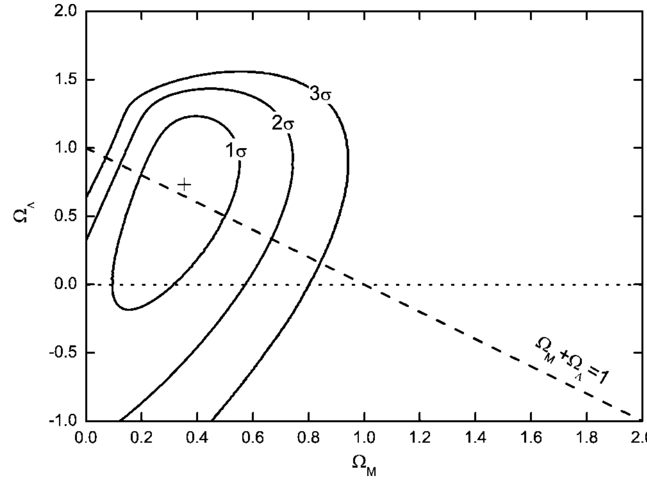

FIG. 3.—Contours of likelihood in the Ω_M-Ω_Λ plane. The plus sign indicates the best fit, and the dashed line is for a flat universe.

$$d_L = c(1+z)H_0^{-1}\int_0^z dz[\Omega_M(1+z)^3 + (1-\Omega_M)(1+z)^{3(1+w)}]^{-1/2}. \tag{7}$$

Figure 4 presents contours of likelihood in the Ω_M-w plane (after marginalizing over h and C). The solid contours consider a prior of $\Omega_M = 0.27 \pm 0.04$ by assuming its Gaussian distribution, similar to Riess et al. (2004). We see $w = -0.84^{+0.57}_{-0.83}$ (1 σ), which is consistent with the value of w expected for a cosmological constant (i.e., $w = -1$).

4. CONCLUSIONS

The $E_{\gamma,\rm jet} \propto E'^{1.5}_p$ relationship with a small dispersion was reported by Ghirlanda et al. (2004) and confirmed in this Letter. The advantages of considering this relationship as a probe of the universe are (1) that GRBs have been detected at redshifts up to $z \simeq 4.5$, (2) that gamma rays suffer from no extinction,

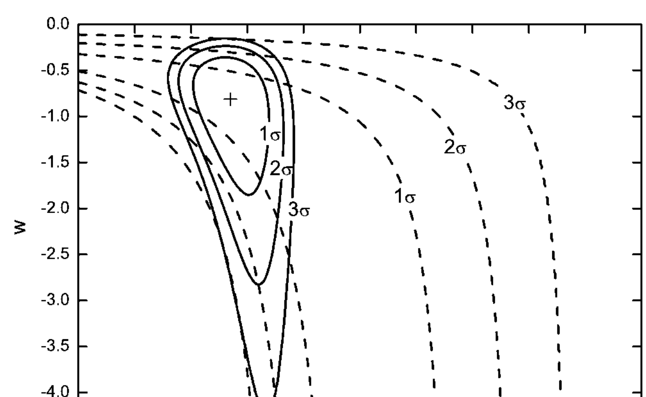

FIG. 4.—Contours of likelihood from the GRB sample (*dashed lines*) in the Ω_M-w plane. The solid contours consider a prior of $\Omega_M = 0.27 \pm 0.04$. The plus sign indicates the best fit.

and (3) that we do not worry about luminosity evolution with redshift. These advantages led us to constrain the mass density of the universe and the nature of dark energy. We found that the mass density $\Omega_M = 0.35^{+0.15}_{-0.15}$ ($1\ \sigma$) for a flat universe with a cosmological constant, and the w parameter of the dark energy EOS $w = -0.84^{+0.57}_{-0.83}$ ($1\ \sigma$). Riess et al. (2004) measured $\Omega_M = 0.29^{+0.05}_{-0.03}$ and $w = -1.02^{+0.13}_{-0.19}$ ($1\ \sigma$) for the current SNe Ia sample. Therefore, our results are consistent with those from SNe Ia.

The upcoming *Swift* satellite with an energy range of 0.2–150 keV will be scheduled for launch in 2004 October (Gehrels et al. 2004). *Swift* is expected (1) to detect more than 100 bursts per year, (2) to observe X-ray and UV/optical afterglows at times of 1 minute to several days after the burst, and (3) to detect very high redshift GRBs. Thus, it is expected that a larger sample of GRBs established by *Swift* provides a further probe of the universe. Such a probe opens up a new window on the cosmic distance scale far beyond the reach of SNe Ia. We call this research field *GRB cosmology*, corresponding to the well-known SN cosmology.

We thank the referee for constructive suggestions and Bing Zhang and Xinmin Zhang for valuable comments. This work was supported by the National Natural Science Foundation of China (grants 10233010 and 10221001), the Ministry of Science and Technology of China (NKBRSF G19990754), the Natural Science Foundation of Yunnan (2001A0025Q), and the Research Foundation of Guangxi University.

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